This full text paper was peer-reviewed at the direction of IEEE Instrumentation and Measurement Society prior to the acceptance and publication.

A protocol for the comparison of reaching gesture kinematics in physical versus immersive virtual reality

Sara Arlati
Institute of Intelligent Industrial Systems and Technologies for Advanced Manufacturing (STIIMA) – Italian National Research Council (CNR)
Department of Electronics, Information, and Bioengineering (DEIB) – Politecnico di Milano
Lecco (LC), Italy
sara.arlati@stiima.cnr.it

Noël Keijsers
Department of Research Sint Maartenskliniek
Nijmegen, Netherlands
n.keijsers@maartenskliniek.nl

Giancarlo Ferrigno
Department of Electronics, Information, and Bioengineering (DEIB) – Politecnico di Milano
Milano, Italy
giancarlo.ferrigno@polimi.it

Marco Sacco
Institute of Intelligent Industrial Systems and Technologies for Advanced Manufacturing (STIIMA) – Italian National Research Council (CNR)
Lecco (LC), Italy
marco.sacco@stiima.cnr.it

Abstract— **Virtual environments are increasingly being used for upper limb rehabilitation in post-stroke patients. However, still there is no clear evidence that the movements performed in virtual reality are comparable to those performed in the physical world from the kinematic point-of-view. The goal of the proposed study is thus to determine if aimed reaching movements made in a 3D ecological and immersive virtual environment – displayed through a Head Mounted Display (HMD) – are comparable to movements performed in the real world. The study foresees the realization of two comparable environmental settings representing the shelf of a supermarket. Three different groups of subjects (healthy young adults, healthy elderly, and post-stroke subjects, n=15 each) are asked to reach 5 times toward 9 targets in 3 different conditions: virtual reality, physical reality, and physical reality while holding a controller. Their movements are tracked with a stereo-photogrammetric motion capture system; movement times, peak velocities, and joint angles are then extracted for analysis. This protocol will allow comparing reaching movements, and also excluding of the effects related to holding a controller. A preliminary trial reveled the feasibility of the protocol, thus the experiment will be carried out in the next months. If results will be encouraging, VR should be considered in rehabilitative treatments as a useful means to elicit patients' motivation, but also appropriate movement synergies, thus promoting a better recovery of upper limb functions.**

Keywords—*rehabilitation, immersive virtual reality, movement analysis, sense of presence*

I. Introduction

Virtual Reality (VR) has recently emerged as a promising technology for the rehabilitation of adults and children with various motor disabilities. VR is an interactive and multisensory experience taking place within computer-generated environment; thus, it provides the users with the possibility to practice in an ecologically valid, safe, controlled, and enjoyable environment [1]. Due to these characteristics, VR has been used in many rehabilitation studies and it has shown its effectiveness in improving patients' clinical and functional outcomes [2–4].

Another important feature of VR is that it generally increases patients' motivation to train, leading to higher treatment adherence [5,6] and performances [7]. This aspect gains a particular significance in the field of rehabilitation, as movement repetition, from the one hand has been proven essential to promote the recovery of motor functions [8], but on the other hand, can easily lead to boredom and frustration.

One of the fields in which VR-based treatments has been applied the most is the rehabilitation of post-stroke patients' upper limb, whose loss of functionalities often results in an important limitation for the re-establishment of the autonomy in activities of daily living (ADL). The effectiveness of VR-based interventions in this field has been proven in previous studies which reported improved outcomes both in terms of motor impairment (e.g., Fugl-Mayer Arm scale) and functional measures (e.g., Functional Independence Measure, Box and Blocks Test, Manual Function Test) [9]. In many cases, the re-training upper limb segments coordination emerged as a fundamental aspect to obtain dexterous movements [10].

Nonetheless, the similarity between the kinematics of movements performed in virtual environments and the kinematics of those performed in the physical world has been assessed only in few cases, and with mixed results. Therefore, there is no guarantee that gestures that are executed in the virtual world are performed as they would be in the physical environment.

Another important aspect related to movements performed in VR is related to Sense of Presence (SoP), i.e., the feeling of *being there* in a computer-generated environment [11]. Indeed, one of the main elements contributing to generate SoP, and thus to increase motivation,

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

978-1-7281-5386-5/20/$31.00 ©2020 IEEE

is *control*, i.e., the control a person has over the task environment or in interacting with the virtual environment (VE) [12]. The more the control, the greater the experience of presence. It appears evident that the feeling of control is strictly related to the usability of the system, and to the naturalness with which the interactions occur.

However, due to system limitations, interactions in VR often require the user to act differently with respect to the behavior that he/she would exhibit in natural world. These unnatural responses may affect a user's SoP and, above all, user's performance, both in terms of single movements' executions, and in terms of the achievement of the general task aims.

Lower performances occur as a result of the higher cognitive load required by unnatural interactions; as they draw from a pool of (limited) cognitive resources (as for dual-task [13]), those resources cannot be used for a concurrent, and possibly more important task, as the completion of the proposed rehabilitative exercise.

Therefore, the design of *natural* interfaces eliciting natural movements represents an essential goal for the implementation of a VR-based rehabilitation program.

In our research group, we developed an immersive VE having the features of a supermarket, and aimed at retraining the reaching movements of post-stroke patients (Figure 1). The Virtual Supermarket – developed for HTC Vive and previously tested in [14] – proposes the user a list of items to buy, and allows him/her to pick them from the displayed 3D shelves.

The interactions (i.e., product picking, dragging and release) occur using the HTC Vive controller, and by pressing and releasing the back trigger. This solution has been preferred to data-gloves a preliminary test performed in the laboratory confirmed the results obtained by Olbrich et al. [15], who found the interactions with data-gloves to be less intuitive. Additionally, the use of a data-glove can constitute an issue for post-stroke patients, as they may have difficulties in wearing it, due to spasticity or muscular hypertonicity.

Figure 1. A screenshot of the application developed for post-stroke patients. Differently from what presented in [14], this version can be used while staying sit. This has been done to ensure the safety of the patients.

Given these premises, in this paper we present a protocol we designed to investigate the kinematic differences of aimed movements in the physical reality, and in an immersive virtual environment with the features of a supermarket. The hypothesis underlying the study is that the *HTC Vive VR headset* is able to return to the user good-quality (visual) feedback, and that this feedback is good enough to allow the interactions – even if performed with the controllers – to occur in a *natural* way. If this is the case, the similarity of the kinematic of movements performed in real vs. virtual environment would be high, meaning that (i) minimum cognitive workload is required to performed the product picking task, and (ii) muscular synergies are correctly elicited, and thus that the rehabilitation exercise is done appropriately. Experiments performed in the next months will tell whether the study hypotheses are true.

II. Related works

Specific studies evaluating the similarities between virtual and real-world movements are sparse and the reported results that are often diverse.

A few studies investigated the similarities between reaching and grasping [16,17] performed in real world and in a 2D virtual environment. Differences in terms of hand trajectory and movement times were found both for healthy and post-stroke subjects enrolled in those studies. The presence of such differences was attributed mainly to the lack of an appropriate perception of depth, due to the use of a 2D environment.

To try to overcome this limitation, more recent studies made use of stereoscopic environments employing either active goggles or a HMDs. Despite the expected reduced misperception of depth, all these studies found some differences when comparing real versus virtual world movements. Reaches were different in terms of hand velocity [17,18], curvature [18], endpoint precision [18], and trunk displacement [19], when considering both healthy subjects or post-stroke patients.

The authors of the abovementioned studies hypothesized that the difference in the kinematics of the two movements were due to the still-persisting misperception of depth [17]; to the lack of familiarity with the VE [16], which resulted in reduced chance of using cognitive cues created on the basis of previous experiences; and to the absence of haptic feedback [19]. To try and limit the misperception of depth, the use of stereoscopic environments represents certainly a key point [18]. Though it is true that some depth-related issues emerged also in studies employing HMDs, it has to be underlined that both Magdalon et al. [19] and Knaut et al. [18] made use of a Kaiser XL50, whose diagonal field-of-view is of 50 degrees. Devices that are currently on the market, as the HTC Vive [20] or the Oculus Rift [21] headsets, have greatly improved this feature, having respectively 145 and 120 diagonal degrees of field-of-view. Therefore, it is plausible that the spatial perception of the 3D environment and, in particular, of depth has improved as well.

Another important point that should not be neglected when evaluating these previous studies is that all the VEs previously employed in studies concerning upper body kinematics were *ad-hoc* developed environments representing just the targets. Though this fact could be understandable given the aim of the studies and the need of having a controlled environment, it also means that not all the potentialities of VR have been exploited. Indeed, a more realistic environment should provide the users with an ecological setting, and also could contribute in enhancing their motivation and thus their performances [2,4].

The protocol we present in the next paragraphs aims at overcoming the limitations of previous studies, and shed new light on the similarity between movements performed in the virtual world, and those performed in the physical reality.

III. Methods

The study is designed as a within-subjects repeated-measurements study, in which participants perform the reaching and transport tasks in three different experimental conditions, i.e.:

- the real world (RW),
- the real world while holding the HTC Vive controller (RWC) and
- the virtual environment (VE).

The RWC condition was introduced to investigate the effect of holding the controller while performing the task.

To control the order effects, subjects' exposure to each condition was randomized. The study will be carried out at the Sint Maartenskliniek in Nijmegen (Netherlands), after the approval of the clinic's Medical Ethical Committee.

A. Participants

Participants are recruited according to the following groups:

- 15 healthy young adults (aged > 18 years, < 40);
- 15 healthy elderly (aged > 65 years);
- 15 post-stroke patients with slight hemiplegia on their dominant side, possibly age-matched with the elderly subjects.

Sample sizes are selected to perform a preliminary study, in agreement to what reported also in previous researches [16,17].

All the subjects must have a good cognitive status; this is assessed administering the Mini-Mental State Examination (MMSE) [22]: we consider a threshold value of> 23 for eligibility. Stroke patients are included if their condition is chronic (i.e., stroke has occurred at least 6 months before), and had a mild to moderate hemiparesis on the affected side; arm functioning is assessed with the *Stroke Upper Limb Capacity Scale* (SULCS)[1], a quick (about 6 min) assessment of arm and hand capacity. The SULCS score has to be at least 6 (i.e., grasping a ball presented from a high angle).

Exclusion criteria for all groups are: inability to provide informed written consent, severe visual or motor impairment, neglect, previous history of seizure or motion sickness. Patients with aphasia or apraxia are excluded too.

B. Equipment

A virtual and the real setup sharing the same features have been used (Figure 2). As the aim is to compare aimed movement toward specific targets, the immersive Virtual

Figure 2. The real (on the left side) and the virtual shelf units (on the right side). In the VE, it is possible to view also the cart, and the shopping list.

Supermarket environment described in [14] was simplified (i) to better control the variability of subjects' movements, and (ii) to allow a realistic reproduction of a real shelf.

Nine different grocery items are placed on the shelves in both cases; they constituted the nine targets to reach and grab, and they are placed about at the hip, trunk and head level of the subjects, in ipsi-, medial and contralateral position. All the products on the shelves have to be reachable by the subject while standing and without stepping forward.

The VE has been developed using Unity 3D [23], and exploiting the functionalities provided by Steam VR and VRTK Unity plug-ins. The interactions with the supermarket items occur using the controller: to grab a product, the subject has to make the controller collide to the object and then pull the back trigger. The release the product once dragged above the cart, occurs when the trigger is released.

Since no haptic feedback could be provided, the controller is vibrating to signal the user that the product has been hit and, thus, that it can be grabbed. This compensation for the lack of haptic feedback has been preferred to other technologies, because haptic technologies are still difficult to integrate in VE, and they require costly devices, which – in the majority of the cases – are invasive and limit the possibilities of natural interaction within the virtual world [24].

The list of the products to pick (all the 9 products on the shelf, always) is presented on the side of the cart, that is placed either on the right or the left side of the user, depending on the user's dominant side. In RW and RWC, lists are printed and placed on a high table positioned on the same spot of the cart.

To ensure that all the targets' positions are the same in all the three conditions of testing, the functionalities of a stereo-photogrammetric motion capture system (VICON [25]) have been integrated in Unity. To do this, VICON *DataStream* SDK [26] was installed to enable the data streaming from Nexus (i.e., the commercial software provided with VICON

[1] Available at: https://rde.maartenskliniek.nl/innovations/sulcs/

Figure 3. A subject performing the task in VE condition. Markers are placed according to Plug-in gate full body model. Additionally, 4 markers are used to detect the height of the real shelves and to align them with the virtual ones (3 are visible).

[27]) to Unity 3D using a client-server architecture. The alignment of the two cameras systems' (i.e., VICON infrared cameras, and HTC Vive base stations) is then performed using the *VR Alignment Tool* plugin [28], and ad-hoc algorithms implemented via Unity scripting. These scripts are needed to adjust translations and rotations of tracked rigid bodies within the VE.

As this systems integration allows for the exploitation of reflective markers' positions in the VE, markers placed at the side of the real shelves (Figure 3) are used to align the virtual ones at the same exact height.

Instead, the horizontal position of the targets is defined relative to the shelf width. In the VR condition, horizontal placements are coded to be always the same, while in RW and RWC conditions, they are identified by notches.

The motion capture system is used also to track user's body movement during each trial. In particular, we use the Full-Body Plug-in Gate anatomical model [29], a model allowing for the reconstruction of the whole body kinematics and based on the placement of 39 markers (Figure 3). Although the focus of this work is only on the upper body, this model has been chosen to exclude the trials in which the user stepped forward to help him/herself with reaching the target item. Data sampling rate for VICON is 100 Hz.

C. *Procedure*

At the beginning of each day of trials, the two cameras' systems are calibrated and aligned. Thus, the heights of the virtual shelves are adjusted according to the real heights.

All subjects are asked to wear tight-fitting shirts (or bra) and shorts so that reflective markers could be appropriately placed on their bodies limiting clothing impact. After having completed the markers' placement and having calibrated the model according to VICON Plug-In Gate procedure, subjects are instructed to stand in front of the shelf (either real or virtual). The distance between the subject and the mid-point of the shelf is equal to the subject arm length: both middle fingers with forward-extended arms have to be touching the mid-shelf; this ensures that subjects are able to reach of all the target items without stepping forward.

Instructions for the completion of the shopping tasks in the three conditions (RW, RWC, VE) are given before the beginning of each condition. The conditions' order is randomized extracting a closed envelope.

Each trial consists in "buying" the 9 items on the shelves following the order with which they are presented on the shopping list. The shopping lists' items order is random too; however, they are coded so that the order of the products to pick is the same in all the conditions, i.e. if the first product to pick from the real shelf is on the higher shelf, contralateral position, the first virtual object to grab is on the higher shelf, contralateral position, too.

In the case of RW, subjects are asked to reach for the physical product adjusting the hand as they would do normally, to grab the product and to place it onto the physical object (i.e., the high table) representing the cart. For RWC completion, the subjects are told to hold the controller and point toward the real product and then pretend to place it in the physical container.

For the VE condition, subjects are instructed on how to use the controllers to interact with the virtual objects. After the explanation, the investigator helps the subject to wear the headset, to adjust the straps and the inter-pupillary distance of the HTC Vive headset. In the case of post-stroke patients, this occurs after having worn a harness.

Before making the very first trial within the VE, each subject has to perform a preliminary trial in the immersive virtual supermarket to familiarize with the environment and the controllers. Within this phase, products on the shelf are different with respect to the targets, and placed in 6 different positions. This trial served to limit the *wow* effect [30], and should help subjects to remember how to deal with the controller [14]. No familiarization was considered needed for the real-world scenarios.

All the subjects are asked to complete five sessions in all the three conditions using their dominant hand (5 sessions x 3 conditions = 15 trials). Between the conditions, subjects are given a couple of minutes to rest, the whole experience lasted from 40 to 50 minutes (comprehensive of marker's placement).

D. *Measures*

The main study outcome is Movement Time (MT). MT was defined as the time elapsed from the movement onset till the movement offset. Movement onsets (and offsets) of each reach are calculated as the times at which the velocity of the marker placed on the subject dominant hand (RFIN or LFIN, according to [29]) surpassed and remained above (or fell and remained below) 0.2 m/s. This threshold is the same used by Stewart et al. [31] in their study.

Secondary outcomes are:

- endpoint velocity, i.e., the maximum hand velocity during reaching and transport phase;
- endpoint trajectory curvature, defined as the ratio between the measured endpoint trajectory length

and the length of a straight line connecting the hand position at movement onset and the target object;

- Ranges of Motion (ROM) of shoulder (abduction-adduction; flexion), and elbow (flexion) of the arm performing the movement; ROM of trunk (forward bending; torsion).

E. Statistical analysis

All the acquired data are analyzed in post-processing using ad-hoc developed routines in Matlab2019a, and exploiting the functionalities of VICON Nexus to extract joint angles, and to calculate markers' position derivatives.

All the collected variables are checked for normality using Shapiro-Wilk test; when normality assumption is not met, data are transformed using an appropriate transformation. The assumption of sphericity is verified using Mauchly test.

2x3x9 ANOVA with between factor *group*, and within factor *condition* and *target position* are performed for each one of the variables of interest. Tukey-Kramer HSD post-hoc pair-wise comparisons are used to assess differences when significant major effects or interactions are observed.

IV. Discussion

The aim of this study is the comparison of the kinematics of aimed movements in immersive VR, with respect to the physical world.

Comparing the kinematics of movements elicited by the task of *reaching of virtual targets* in an ecological environment, still represents an open point, and disclosing new similarities as a result of the increased (visual) quality of devices, could represent a key point to promote the use of VR for upper-limb rehabilitation. In this case, in fact, the rationale pushing the use of VR for rehabilitative interventions would be related not only to motivation, but also to the elicitation of appropriate movement synergies.

A. Expected results

We expect the young adults to perform quicker movements with respect to elderly; and all healthy subjects to perform better than post-stroke subjects, in agreement of what mentioned in the existing literature.

Additionally, we hypothesized that the use of VR would introduce differences in the outcome variables for all groups, but that these differences could be mitigated with respect to previous studies thanks to the advent of good-quality HMDs. We expect VR to influence the performance of the proposed exercise to different extents for each group: post-stroke would be the more influenced population, while elderly and young adults will follow.

Finally, we expect to find an effect of target position, and to identify increased MTs, and increased curvature for contralateral targets, in agreement to what found by Knaut et al. [18]. Reaching contralaterally located targets is indeed more difficult, as the arm has to cross the body midline in a complex coordination of elbow extension with shoulder flexion and horizontal adduction; thus, we expect this complexity to be emphasized by VR.

B. Future works and perspectives

A preliminary test performed enrolling 1 healthy one subject (shown in Figure 3) allowed determining the feasibility of the presented protocol.

In the next future, the presented study will be carried out at the Sint Maartenskliniek (Nijmegen, NL), with the presence of a physical therapist that will be required for (i) the assessment of the post-stroke subjects' arm function, (ii) providing support to wear a harness prior to study commencement, and (iii) for the supervision and the eventual interruption of all the sessions.

This has been considered a necessary safety measure, though we do not expect the arousal of cyber-sickness, as no sensory mismatch is present in the immersive VE, and as the whole VR experience lasts less than 10 minutes [32]. If any side effect would arise, the session would be interrupted immediately, and the person would be supervised until the disappearance of all symptoms.

If the results of this study will be positive, they would be indeed encouraging for the exploitation of immersive VR in rehabilitation programs aimed at the improvement of upper limb functions.

Clearly, this study would not answer the key question about the degree of similarity that movements performed in VR and those made in the physical world should have to obtain functional gains; further studies will be thus required.

However, as evidence shows that task-specific training, repetitions and motivation are fundamental aspects to obtain better rehabilitation outcomes [3,33], we believe that VR should continue to be considered as a promising technology, and as a means worthy of investigation for the optimization of rehabilitation interventions.

V. Acknowledgments

The authors would like to acknowledge the support of Eng. Gabriele Paolini (GPEM srl), whose contribution has been essential for the implementation of the data stream from VICON Nexus to Unity 3D.

VI. References

[1] A.A. Rizzo, M. Schultheis, K.A. Kerns, and C. Mateer, "Analysis of assets for virtual reality applications in neuropsychology," Neuropsychological Rehabilitation, vol. 14, 2004, pp. 207–239.

[2] D. Corbetta, F. Imeri, and R. Gatti, "Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review," Journal of physiotherapy, vol. 61, 2015, pp. 117–124.

[3] K.E. Laver, S. George, S. Thomas, J.E. Deutsch, and M. Crotty, "Virtual reality for stroke rehabilitation," Cochrane database of systematic reviews, 2015.

[4] Y.-Y. Liao, Y.-R. Yang, S.-J. Cheng, Y.-R. Wu, J.-L. Fuh, and R.-Y. Wang, "Virtual reality–based training to improve obstacle-crossing performance and dynamic balance in patients with Parkinson's disease," Neurorehabilitation and neural repair, vol. 29, 2015, pp. 658–667.

[5] K. Brumels, T. Blasius, T. Cortright, and B. Solberg, "Comparison of efficacy between traditional and video game...," Clinical Kinesiology, vol. 62, 2008, pp. 26–31.

[6] D. Meldrum, S. Herdman, R. Vance, D. Murray, K. Malone, D. Duffy, A. Glennon, and R. McConn-Walsh, "Effectiveness of Conventional Versus Virtual Reality-Based Balance Exercises in Vestibular Rehabilitation for Unilateral Peripheral Vestibular Loss: Results of a Randomized Controlled Trial," Archives of Physical Medicine and Rehabilitation, vol. 96, 2015, pp. 1319–1328.

[7] M. Farrow, C. Lutteroth, P.C. Rouse, and J.L. Bilzon, "Virtual-reality exergaming improves performance during high-intensity interval training," European journal of sport science, 2018, pp. 1–9.

[8] M.K. Holden, "Virtual environments for motor rehabilitation," Cyberpsychology & behavior, vol. 8, 2005, pp. 187–211.

[9] A. Henderson, N. Korner-Bitensky, and M. Levin, "Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery," Topics in stroke rehabilitation, vol. 14, 2007, pp. 52–61.

[10] M.F. Levin, E.C. Magdalon, S.M. Michaelsen, and A.A.F. Quevedo, "Quality of Grasping and the Role of Haptics in a 3-D Immersive Virtual Reality Environment in Individuals With Stroke," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 23, 2015, pp. 1047–1055.

[11] G. Riva, F. Davide, and W.A. IJsselsteijn, Being there: Concepts, effects and measurements of user presence in synthetic environments., Ios Press, 2003.

[12] B.G. Witmer and M.J. Singer, "Measuring presence in virtual environments: A presence questionnaire," Presence, vol. 7, 1998, pp. 225–240.

[13] P. Plummer, G. Eskes, S. Wallace, C. Giuffrida, M. Fraas, G. Campbell, K. Clifton, E.R. Skidmore, and others, "Cognitive-motor interference during functional mobility after stroke: state of the science and implications for future research," Archives of physical medicine and rehabilitation, vol. 94, 2013, pp. 2565–2574.

[14] M. Mondellini, S. Arlati, S. Pizzagalli, L. Greci, M. Sacco, and G. Ferrigno, "Assessment of the usability of an immersive virtual supermarket for the cognitive rehabilitation of elderly patients: A pilot study on young adults," 2018 IEEE 6th International Conference on Serious Games and Applications for Health (SeGAH), IEEE, 2018, pp. 1–8.

[15] M. Olbrich, H. Graf, J. Keil, R. Gad, S. Bamfaste, and F. Nicolini, "Virtual reality based space operations–a study of ESA's potential for VR based training and simulation," International Conference on Virtual, Augmented and Mixed Reality, Springer, 2018, pp. 438–451.

[16] D.G. Liebermann, S. Berman, P.L. Weiss, and M.F. Levin, "Kinematics of reaching movements in a 2-D virtual environment in adults with and without stroke," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 20, 2012, pp. 778–787.

[17] A. Viau, A.G. Feldman, B.J. McFadyen, and M.F. Levin, "Reaching in reality and virtual reality: A comparison of movement kinematics in healthy subjects and in adults with hemiparesis," Journal of NeuroEngineering and Rehabilitation, vol. 1, 2004.

[18] L.A. Knaut, S.K. Subramanian, B.J. McFadyen, D. Bourbonnais, and M.F. Levin, "Kinematics of Pointing Movements Made in a Virtual Versus a Physical 3-Dimensional Environment in Healthy and Stroke Subjects," Archives of Physical Medicine and Rehabilitation, vol. 90, 2009, pp. 793–802.

[19] E.C. Magdalon, S.M. Michaelsen, A.A. Quevedo, and M.F. Levin, "Comparison of grasping movements made by healthy subjects in a 3-dimensional immersive virtual versus physical environment," Acta psychologica, vol. 138, 2011, pp. 126–134.

[20] HTC Vive VR System, available at: https://www.vive.com/us/product/vive-virtual-reality-system/.

[21] Oculus VR, https://www.oculus.com/.

[22] M.F. Folstein, S.E. Folstein, and P.R. McHugh, "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician," *Journal of psychiatric research*, vol. 12, 1975, pp. 189–198.

[23] Unity Real-Time Development Platform, available at: https://unity.com/.

[24] H. Culbertson, S.B. Schorr, and A.M. Okamura, "Haptics: The present and future of artificial touch sensation," Annual Review of Control, Robotics, and Autonomous Systems, vol. 1, 2018, pp. 385–409.

[25] VICON Motion Capture System, available at: https://www.vicon.com/.

[26] VICON datastream SDK, available at: https://www.vicon.com/software/datastream-sdk/.

[27] Vicon Nexus regulatory information. Available at: https://docs.vicon.com/display/Nexus27/Vicon+Nexus+regulatory+information.

[28] VICON Alignment Tool, available at: https://www.vicon.com/software/utilities-and-sdk/vr-alignment-tool/.

[29] Plug-in Gate Reference Guide, available at: https://docs.vicon.com/display/Nexus27/Plug-in+Gait+Reference+Guide.

[30] S. Arlati, D. Spoladore, D. Baldassini, M. Sacco, and L. Greci, "VirtualCruiseTour: An AR/VR Application to Promote Shore Excursions on Cruise Ships," International Conference on Augmented Reality, Virtual Reality and Computer Graphics, Springer, 2018, pp. 133–147.

[31] J.C. Stewart, J. Gordon, and C.J. Winstein, "Planning and adjustments for the control of reach extent in a virtual environment," *Journal of NeuroEngineering and Rehabilitation*, vol. 10, 2013.

[32] J. Hakkinen, T. Vuori, and M. Paakka, "Postural stability and sickness symptoms after HMD use," IEEE International Conference on Systems, Man and Cybernetics, IEEE, 2002, pp. 147–152.

[33] M.F. Levin, L.A.M. Knaut, E.C. Magdalon, and S. Subramanian, "Virtual reality environments to enhance upper limb functional recovery in patients with hemiparesis," Studies in Health Technology and Informatics, 2009, pp. 94–108.